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KNOWLEDGE ACQUISITION FOR A SIMPLE EXPERT CONTROLLER

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16. Abstract

A method is presented for process control which has the properties of being incremental, cyclic and top-down. It is described on the basis of the development of an expert controller for a simple, but non-linear control route. A quality comparison between expert controller and process operator shows the ability of the method for knowledge acquisition.

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KNOWLEDGE ACQUISITION FOR A SIMPLE EXPERT CONTROLLER

B. Bieker

In many processes, especially in process engineering, the heuristic precedures often used industrially, do not provide a successful control, on the other hand, the theoretically founded proposed method to set up a sufficiently accurate process model, also fails. Usually, these processes are conducted by process operators with frequently satisfactory result. In these cases it seems obvious to work out the control strategy of the process operator (knowledge acquisition) and to implement it by using modern computer equipment. So in this report, a so-called active-verbal knowledge acquisition is treated as a successful method for a certain class of control tasks.

The presented method has the properties of being incremental, cyclic (cycle of hypothesis formation and testing) and top-down. It is described on the basis of the development of an expert controller for a simple, but non-linear control route. A quality comparisor between expert controller, process operator and a conventional PI controller shows the ability of the method for knowledge acquisition.

1. Introduction and Overview

In many processes, especially those of process engineering, the heuristic procedures frequently used in industry to develop a control method, have not been successful. The theoretically based proposed methods fail due to the lack of a sufficiently accurate process model needed for a specific description of the control

quality. The reason for this is that a part of the fundamental physical/chemical laws is not known and also a linear behavior model is not sufficient for these processes.

Many of these processes are thus being run today by process operators with frequently satisfactory results. So the idea is to use the process operator as a direct pattern for a control device, or to work out its control strategy subordinate to his control behavior (knowledge acquisition) and to implement this by using modern computer equipment.

A series of interesting processes have an inertial, dynamic behavior corresponding to the time scale of conscious human information processing. In [1] it is shown that the passive verbal knowledge acquisition on-line--which contains essentially the evaluation of verbal protocols of "vocal thinking" of the process operator in process control--does not provide the desired result. Of the possible alternatives, the use of a "verbal communication channel" is appropriate for knowledge acquisition.

After a brief presentation of control tasks based on the ideas of active knowledge acquisition, the cyclic procedure is discussed below. The significant reaction on the control behavior found herein is taken into account by a top-down procedure embedded in the cyclic process. Thus assures a "careful linkage with the process operator." After an overview of the suggested method, it will be further explained based on the mentioned control task. But for reasons of brevity, this cannot be done in detail, rather only by pulling out the most essential aspects.

Finally, the success of the method is expounded by a comparison of process operator, expert controller and a conventional PI controller based on time sequences.

2. Characterization of the Control Task

The control task will be briefly outlined here; it is described in more detail in [1] in section 5a "Basis of Performed Laboratory Investigations."

Control Route

-SISO route (Single Input, Single Output)

-Implementation via structured equipment (laboratory fill level control route).

-Non-linear behavior; s-curve of all jump responses (u → x, zi → x). Delay time about 0.5 minutes; rise time about 6 minutes; vibration time about 10 to 25 minutes, depending on level and degree of calcification of the system; used scan time 3 s.

-Jump-like interference profiles.

Presentation of Process Information

Time window or trend representation of setting, control and regulation parameters; length of time window about 25 minutes.

Task of Process Operator

To reach the desired value with segmented, constant control quantity by manual regulation and to hold this value (in spite of interference).

3. Fundamentals and Task of Active Knowledge Acquisition

Two requirements of a method for knowledge acquisition are: Its control strategy should:

-be computer implemented and

-necessarily yield nearly the same quality as the process operator

Given the task of the process operator (PB) as a functional element in the closed loop, it seems necessary to choose him as a direct, though idealized pattern, for a computer-implemented control strategy. Because only under this assumption can a certain guarantee of stability and quality of the final, implemented control strategy be obtained.

The starting point for active knowledge acquisition is the relative finding that passive verbal knowldege acquisition on-line cannot deliver any facts, rather only hypotheses to the control strategy subordinate to the PB. So the knowledge acquisition can be presented as follows: Verbal protocol, attendant time plots and notices allow the knowledge engineer (KE) to set up off-line hypotheses which are tested experimentally. The hypotheses could be perhaps (production) control of the type

WHEN <Situation>

THEN <Action>.

One possible experiment is to confront the PB in the process control with the hypotheses corresponding to the particular process situation. The PB's task is to confirm or reject the hypotheses.

If this process is put into practice, then we find that the PB is inherently incapable of confirming ("yes, I think so too") or rejecting the hypotheses. Moreover, qualitative changes in control quality and in setting sequences can be established. This phenomenon can be explained since in this manner the PB's control behavior underlying his decision processes were not known and he now begins at least in part to operate in accord with the hypotheses known to him. In addition, he is stimulated to put his conduct critically under the magnifying glass and to systematize it; this too leads to a more or less severe modification of his control behavior. So the engineer is facing the little-known situation where the investigation of an object necessarily leads to a severe change in the object. This process might previously be viewed as undesirable. But since it is a learning process which on average causes an increase in control quality, the evaluation is converted in many cases into its opposite.

Figure 1 shows the basic property of active knowledge acquisition, namely the described cyclic procedure (see also figures 1 and 2 in [1]). The designation "active" was chosen since the KE now need not absorb passive knowledge, but generates active hypotheses to acquire knowledge.

The task of active knowledge acquisition is to transform the unconscious control strategy of a PB into a conscious, verbally expressed control strategy with no significant loss of quality. Since the PB begins at least partly to operate the process based on the required hypotheses, their generation can also be viewed as

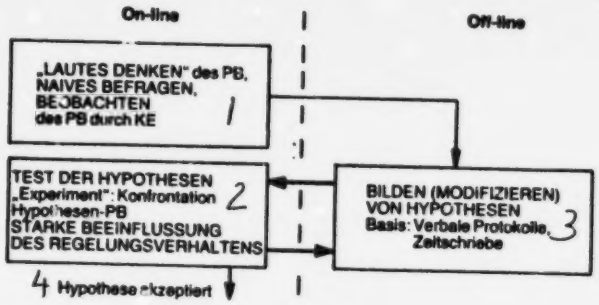


Fig. 1. Basic Ideas and Properties of Active Knowledge Acquisition

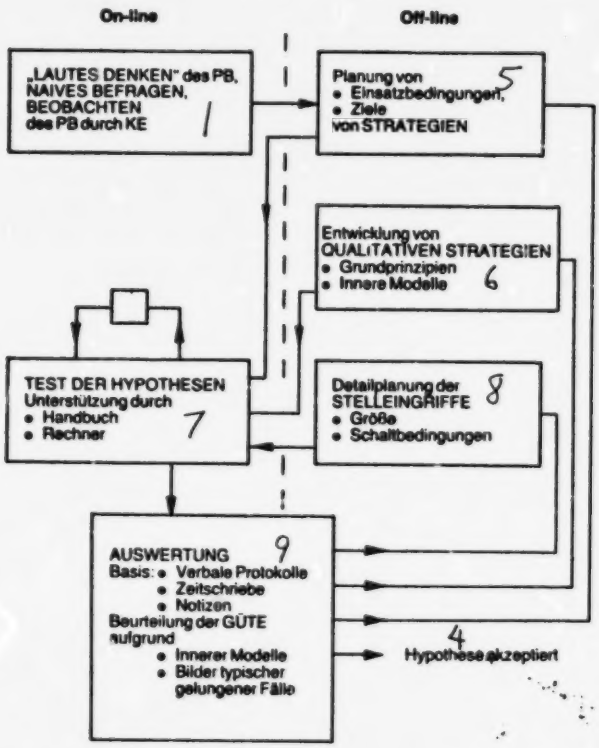


Fig. 2. Overview of the Process of Active Knowledge Acquisition in Inertial Processes.

Key: 1-thinking out loud by PB, naive questions, observation of PB by KE 2-test of hypotheses, "experiment", confrontation of hypotheses/PN. Strong influence on control behavior 3-forming (modifying) hypotheses. Basis: verbal protocols, time plots 4-hypothesis accepted 5-planning of goals and conditions for use of strategies 6-evolution of qualitative strategies, basic principles, internal models 7-test of hypotheses, supported by handbook and computer 8-detailed planning of manipulations, magnitude, conditions

plans for process operation. This shows clearly that there is a danger of incorrect planning and manipulation of the process events. This fact must be taken into account by a careful generation of hypotheses. Active knowledge acquisition achieves this by a top-down development of hypotheses and thus of the computer-implemented control strategy.

4. Top-Down Procedure

A top-down procedure makes it easier to evaluate the completeness of a process. This applies for the development of a computer-implemented control strategy in particular. For an unstructured collection of several hundred to several thousand rules--expected for the control strategy--one can hardly tell whether they will contain contradictions, duplications or gaps. For on-line, real-time tasks, the easy discernment of such weaknesses in a system of rules is naturally of greatest importance.

The main reason for the top-down procedure is the fundamental finding from the completed investigations, that the adjusting manipulations of the PB are frequently in close relation (context) (see also [1]). Related manipulations are elements of a strategy. Strategies are begun and concluded by process situations--like "severe malfunction" or "minor jump in control quantity". These

findings obtained in the investigations can be summarized in the following definitions.

Definition 1: The control strategy of the experienced process operator is a quantity of (partial) strategies. (Note: "Control strategy" is meant here as a separate concept from "strategy".)

Definition 2: A strategy is a structuerd quantity of possible adjusting manipulations.

Regarding the chronological sequence of application of strategies, any possible combination may occur. The applications are initiated and concluded by process situations allocated to the strategies, or by changes in objective of process control (in the following example in section 6, that is changes in desired value). Process situations are on the one hand process events in the form of malfunctions and on the other hand are partial goals achieved by the use of strategies.

Adjusting manipulations are not mutually independent with regard to their chronological sequence; the structure of a strategy establishes possible sequences of adjusting manipulations. Strategies do determine the context of adjusting manipulations and thus are the basis for "understanding" the sequence of adjusting manipulations (this is of great importance for teaching of other PBs who are to take over the found control strategy).

So it is evident that for a top-down process and to determine the context, we begin with the acquisition of knowledge at the stragety level.

5. Overview of Active Knowledge Acquisition

The method of active knowledge acquisition is not a detailed set of instructions, rather it is merely a guideline. On the one hand, it is important that it does not yet have enough practical applications. On the other hand, owing to the complexity and individuality of the person of the process operator, the level of a guideline cannot be abandoned. Loosely formulated: A "system of equations" is never obtained where a process operator can be inserted and "automatically" a computer implemented control strategy comes out.

The actual acquisition of knowledge is preceded by working out two preparatory problems. First, the PB and KE must establish a common language and terminology. This includes the definition of tasks and requirements of the process control. At present, it is indespensible for the KE to know the structure and mode of operation of the process. Then the KE must have precise knowledge of the information interfaces between PB and process--a point which may be surprising at first glance, but according to experience it is a non-trivial matter. Owing to this knowledge, the information interface should be modified--the method described here proceeds from the time window representation of process information constantly needed for the control.

Similarly, these two problems run through the entire knowledge acquisition. New concepts are defined again and again, and the selection of process information for the process control

Fig. 3

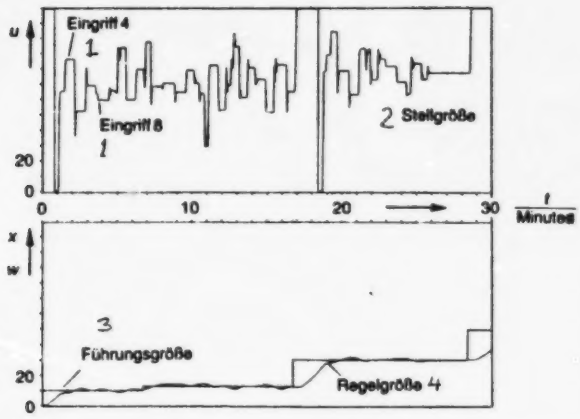


Fig. 3. Profile of an Experienced PB in the Named Control Task

Key: 1-manipulation 2-adjusting quantity 3-control quantity 4-control quantity

must be clarified (under what conditions is what information source relevant).

With reference to fig. 3, an overview will be presented of the active acquisition of knowledge. It shows in particular how the top-down approach is embedded in the cyclic procedure.

At the top or first level, the KE and PB determine the practical conditions or initiating process situations and goals of the strategies. The basis for this is "thinking out loud" by the PB, naive questions by the KE and observations of the PB about the process control.

At the second level, qualitative strategies are worked out. This interim step is important since it corresponds to a careful formation of hypothesis (hypotheses are almost never rejected entirely, rather only refined). It also corresponds to an under-

standing of the strategies of the PB based on his internal model of the process.

At the third level, the quantities of adjusting manipulations and the switch to the next manipulation are planned and tested.

The sharp division of the top-down process into three levels cannot always be rigidly retained. For instance, additional goals of strategies may arise in the evolution of qualitative strategies. Usually when working out a strategy, the interaction of two neighboring levels will occur. Sometimes even "revolutions" will pop up: The PB obtains such deep insights due to the acquisition of knowledge, that he modifies a strategy so that its qualitative description and detailed planning of adjusting manipulations must be performed anew. The resultant necessary acquisition of knowledge is surprisingly fast to implement. Since the implementation effort increases due to the frequently increasing level of detail of the strategy, a decision has to be made whether or not the "old" strategy should be retained.

The on-line test of the hypotheses is supported at levels 1 and 2 by a handbook, while at level 3 a quantitatively produced proposal system is needed for the particular manipulation to be used. The handbook can be implemented in a computer; the proposal system is best if implemented in a computer. Thus, a sharp hypothesis formation and a hard test are required. Moreover, a switch to closed-loop operation is prepared.

Modification of hypotheses is based on a quality evaluation of the on-line test. The quality evaluation is allowed essential-

ly by the internal model of the PB of the process behavior; these are then also an aid for specific modification of the hypotheses.

Modification of hypotheses is usually performed off-line. If there is enough time in a process control, it can also be done on-line; the unnamed small block in fig. 2 indicates this. This case is rare, in our experience.

A third property of the process is incremental knowledge acquisition. The control strategy is constructed in steps from strategies and manipulations. It may happen that a strategy is already present in an on-line-like version, while another one is at level 1 of knowledge acquisition.

6. Active Knowledge Acquisition for Parameter Control

The active acquisition of knowledge will now be discussed with reference to the control task sketched in section 2 and explained by examples. For reasons of brevity, the cyclic procedure can only be indicated.

Figure 3 shows a typical sequence of a PB (Note: We are dealing with another person than in fig. 5 in [1]. The points of the manipulation profile of fig. 3 are caused by an adjusting process to a particular value). The presentation of process information on a raster graphics screen is important. Horizontal or vertically neighboring, lighted pixels are called "bars". A time profile of control quantities consists of a number of bars of different length. Since vertical bars do not occur below, the word "bar" can be used without danger of misunderstanding. It is important

that the PB "think in bars and pixels"; the slope will be determined by lengths of bars. This may seem trivial, but the author took some time to discover that the "pixels" were not only a verbal means of description to the PB, but also the basis of his decisions on manipulations.

a) Goals and Conditions for Using the Strategies

Goals and conditions for using the strategies will be described qualitatively at first. The delimitation of strategies through the conditions of use and goals is frequently subject to a cyclic process. It is useful to name the strategies. The quantitative description of conditions for use can lead to an increase in the number of produced strategies, due to their refinement.

In the present control problems, the PB used four strategies which he called the:

(1) Double pulse strategy for desired value jumps

(2) Double pulse strategy for malfunctions

(3) Box strategy and

(4) Fine strategy.

Applications of (1) and (3) are shown in fig. 3. Item (2) will not be discussed below, so that (1) is called simply the "double pulse strategy" for brevity. Goals and conditions for use are stated for (1) and (3).

Douple Pulse Strategy

1. Concept

Conditions for use: Large jumps in desired value

Goal: Average control difference (Xd ≡ 0 is possible, but improbable. For average control difference, the box strategy will be used; for small control difference, the fine strategy is used).

2. Concept

Conditions for use: Upward jumps in desired value, when Xd $\geq$ 9 pixels at the time of the jump. Jumps in desired value downward when Xd $\leq$ -11 pixels at the time of the jump.

Goal: As above.

Another refinement which will not be discussed here, takes into account the rise in the profile of control quantities at the time of the jump.

Box Strategy

Conditions for use:

-Current average control difference, due to average jump in desired value or to any other cause (e.g. after performing the double pulse strategy).

-Future, expected average control difference (for currently small control difference), due perhaps to a small or medium malfunction.

Goals: Small control difference, damping of vibrations (induced by manipulations), estimation of stationary required desired value.

The latter goal has a certain overlap at levels 1 and 2 of the acquisition of knowledge; this is explained in section 6b.

The refinement of conditions for use and detailing of goals are omitted here.

Figure 3 shows the application of the double pulse strategy three times, twice completely. The profile of adjusting quantities occurring in between, is provided by the box strategy.

b) Qualitative Strategies

-Classification of Strategies

The first step in evolution of qualitative strategies is to clarify whether the particular strategy is an absolute or a relative strategy.

Definition 3: A strategy is called absolute when the manipulations are performed relative to a physically established zero point.

Definition 4: A strategy is called relative when the manipulations are performed relative to a reference line imagined by the process operator.

These two definitions are surely trivial in content. But for acquisition of knowledge it is of decisive importance to find out which class to use for a strategy. The double pulse strategy is an absolute strategy; the box strategy is a relative strategy. The reference line imagined by the PB is the stationary adjusting value considered necessary by him (abbreviated: SES). Figure 4 contains the same profile as fig. 3; the adjustment profile is

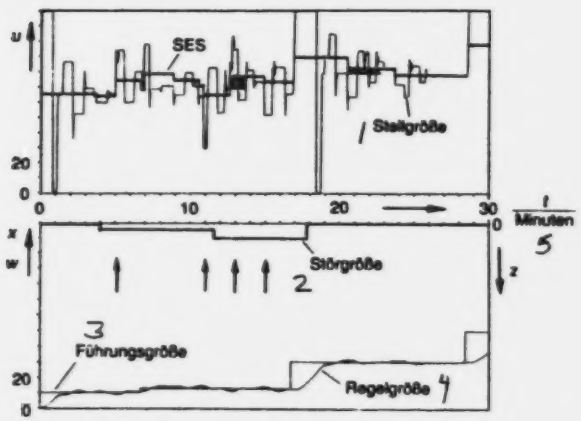


Fig. 4. Explanation of a Relative Strategy

Key: 1-adjusting quantity 2-interference quantity 3-control quantity 4-control quantity 5-minutes

supplemented by the SES profile which was taken from the pertinent verbal protocols. We see that the PB repeatedly shifts the reference line.

Strategies can be further divided into chain-like strategies and network-like strategies.

Definition 5: A strategy is called chain-like or sequential, when the adjusting manipulations belonging to the strategy always have a fixed sequence during application of the strategy; only the switch to the subsequent adjusting manipulation is determined by the process situation.

So events occur in a sequence like those in a process-controlled sequence-control.

Definition 6: A strategy is called network-like when both the type of the particular, next manipulation, and also the switching to it, are dependent on the particular process situation.

It is best to order the manipulations belonging to a strategy under an abstract viewpoint, so that the number of abstract manipulations belonging to a strategy is finite, even though on a numeric level all adjusting values of a continuous adjusting range can occur.

Double Pulse Strategy

Absolute, chain-like strategy.

Manipulations (abstract): "Gas pulse", "Brake pulse", SES.

Box Strategy

Relative, network-like strategy.

While an absolute, chain-like strategy is the simplest case, a relative, network-like strategy represents the most difficult case. The abstract description of manipulations can only be attained by working out the basic principle of such a strategy. Rotation and angle point are the "internal model" here. This means the model conceptions which the PB understands from the process and its behavior.

-Internal Model

When using the term "internal model", one may not assume that the PB can explain it off-line (excepting the geometric structure of the process). It must be enquired incrementally of the PB. It is a concept or model conceptions of the PB.

The questioning technique to be used to obtain the internal model can be characterized by the form

WHEN <Action>

THEN <Expected situation>.

In every manipulation by the PB, the situation expected by him, i.e. the profile of control quantities expected for the time after the manipulation, is examined. The appendix contains a verbal protocol which shows the use of this question technique--still in a very qualitative stage.

It must be stressed that the internal models are relatively rough. In addition, they are valid only within the particular strategy; in particular these models apply only for a limited time interval which begins at the timepoint of a manipulation. Under various strategies of a PB, usually various internal models are present; different process operators have different internal models of the same process, provided they have different strategies. Internal models thus cannot be used for conventional development of a controller.

By means of the internal model, a certain evaluability of the local control quality and of the expediency of nearly every manipulation is possible. Thus a decision can be made of whether a hypothesis can be accepted and how it is to be modified. Notice also that the PB develops malfunction models for typical malfunctions which also are valid only for a limited time interval.

The process situation following a manipulation naturally need not correspond to the expected situation. Unexpected situations indicate the effect of a malfunction or wrong estimation of a parameter (e.g. of the SES) of the current strategy by the PB. In

each of these cases, an immediate manipulation is required. Either a manipulation is initiated within the current strategy or the application of a strategy (the same or a different one) begins anew. Figure 4 shows the profile of an interfering parameter. For a time from 0 to 20 minutes, we see where the PB recognizes a malfunction (only the change in an interfering quantity is a malfunction) according to a verbal protocol. It is evident that he makes two mistakes. In one case owing to faulty thinking, the SES slides out (at time "13 minutes" about within a period of 1 minute not further delimined by the verbal record). The PB would necessarily have to conclude the onset of a malfunction.

-Box Strategy

Internal model: Greatly simplified an "I-Tt-model" (integrated with test time) is present.

Basic principle: The core of the box strategy is constructed at the abstract level by five manipulations: first, second, third and fourth box pulse, SES.

Figure 5 explains the basic principle of this strategy. An approximately average control difference is present; as adjusting value, the SES is adjusted. To eliminate the control difference, the PB performs the (relative) manipulation Δu_1. He expects that the control difference changes very little until passage of the process reaction time (a constant Tt here). After passage of the process reaction time (PRZ) he expects an appropriate rise in the direction of the desired value. The length of the first bar after

passage of the PRZ can serve as a measure of this. By using this rise, the switching timepoint can be established at the predetermined, second box pulse; an excessive overshoot is to be avoided. For vibration damping, the second box pulse is half as large as the first box pulse, so it is $\Delta u_2 = -0{,}5 \cdot \Delta u_1$. After passage of the PRZ, the PB expects a bar which is longer than its predecessor. Next, an increase should occur half as large as the one belonging to the first box pulse. The method is continued correspondingly until adjustment of the SES.

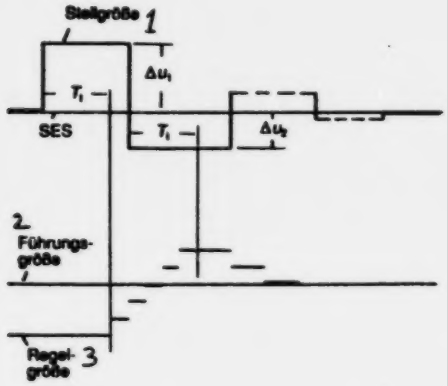


Fig. 5. Explanation of the Meaning of "Internal Model"

Key: 1-adjusting quantity 2-control quantity 3-control quantity

This simple principle is the basis of the box strategy. One prerequisite is that the SES which is an estimate, be accurate. As fig. 4 shows, this is rarely the case. Secondly, a malfunction can begin or have begun which likewise requires a shifting of the SES. With the prevailing rise, the PB has a measure for the needed shift, i.e. a new estimated value for the SES. The PB uses the box strategy not only to correct control differences, but with

the same weight to estimate the SES. Figure 4 shows how often the SES is shifted under some circumstances.

Besides the shift of the SES, in most cases the sequence must be abandoned. It is begun anew farther forward, frequently only after intermediate insertion of other (abstract) manipulations.

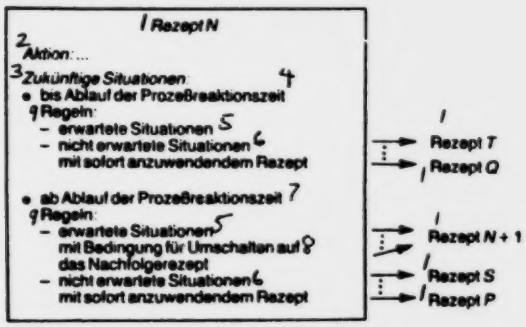


Fig. 6. General Structure of the Recipe

Key: 1-recipe 2-action 3-future situations 4-until passage of the process reaction time 5-expected situations 6-unexpected situations with immediate applied recipe 7-after passage of the reaction time 8-with condition for switching to the following recipe 9-rules

The expected and unexpected situations linked with the manipulation can be combined into a so-called recipe. Its basic structure is illustrated in fig. 6 for a process with delay time. The subdivision indicates that until passage of the process reaction time, the next to last manipulation, and after passage of the process reaction time, the last manipulation is active.

The questioning technique allocated successfully to a manipulation is thus based on the form

WHEN <Action>

THEN <Expected situation>,

and not, as usually expected, on the form

WHEN <Situation>

THEN <Action>.

-Qualitative Strategies

The last step at the second level of knowledge acquisition is the formulation of the qualitative strategies themselves. This is not possible for the box strategy. It is indicated for the double pulse strategy.

WHEN large jump in desired value,

THEN double pulse strategy.

Recipe "Gas pulse".

Action: u = u max.

Future situations:

.
.
.

Expected situations after passage of the process reaction time:
Control quantity moves toward the desired value

WHEN the control quantity reaches the value x-switch

THEN recipe "Brake pulse".

.
.
.

This example illustrates that in principle, rules of the type

WHEN <Situation>

THEN <Action>

are present.

c) Planning and Testing of Manipulations

This level contains the work flow of knowledge acquisition. On the one hand, the manipulations (recipes) are to be determined quantitatively by quantity, on the other hand, within the recipe, rules of the type

WHEN <Expected situation>,

THEN nothing,

or

WHEN <Expected situation>,

THEN <Subsequent recipe>

are to be developed.

An implemented recipe will be shown in a subsequent paragraph.

7. Supplemental Comments

-Presentation of the Process Information

A time window representation was selected. It offers the great advantage described below. Time plots serve off-line, for generation of hypotheses. So these are necessarily permeated with properties of curve segments, like slopes. If the same type of on-line information representation is present, then the hypotheses are directly applicable and testable. If an on-line instantaneous-value display is used, this is no longer the case. A prerequisite for the time window representation is however, the reproduction of the quantization of the screen in the time plots; the identity of the scales is very expedient.

-Computer Support

At the third level of knowledge acquisition, owing to the access time to the acquired knowledge, computer support is indespensible. The cyclic procedure in active knowledge acquisition requires e.g. an easy modification of the implementation. This problem of knowledge representation will be discussed in the following section.

8. Evaluation

The illustrated method of active knowledge acquisition has as its core a cyclic procedure. In [2] a basically similar procedure is suggested. The acquisition of procedural knowledge, as a control strategy is, causes special difficulties in comparison to the acquisition of declarative knowledge (relations between properties of objects). So in procedural knowledge, it becomes necessary to use a cyclid procedure. Moreover, a certain impression of "Making a compu'er-implemented control strategy" comes up. But what is "made" and what is transformed from the unconscious into the conscious, unfortunately cannot be decided today, since the control strategy of the PB--when stated carefully--is not available at the beginning of knowledge acquisition.

In the final analysis, success is decisive. The presented method of knowledge acquisition using the fundamental control task is illustrated with reference to figures 7 to 9. The control strategy comprises the four strategies cited above with about 20 recipes in each. Since there are about 5 to 6 rules to each

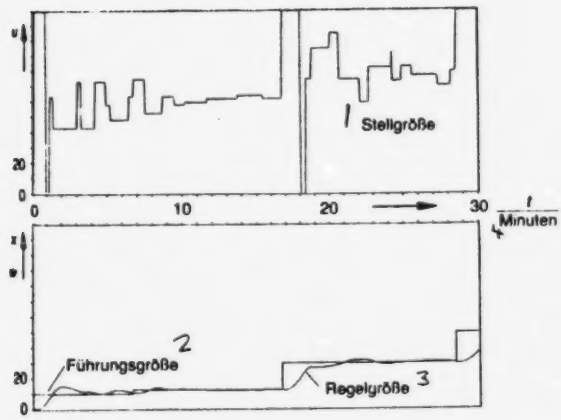
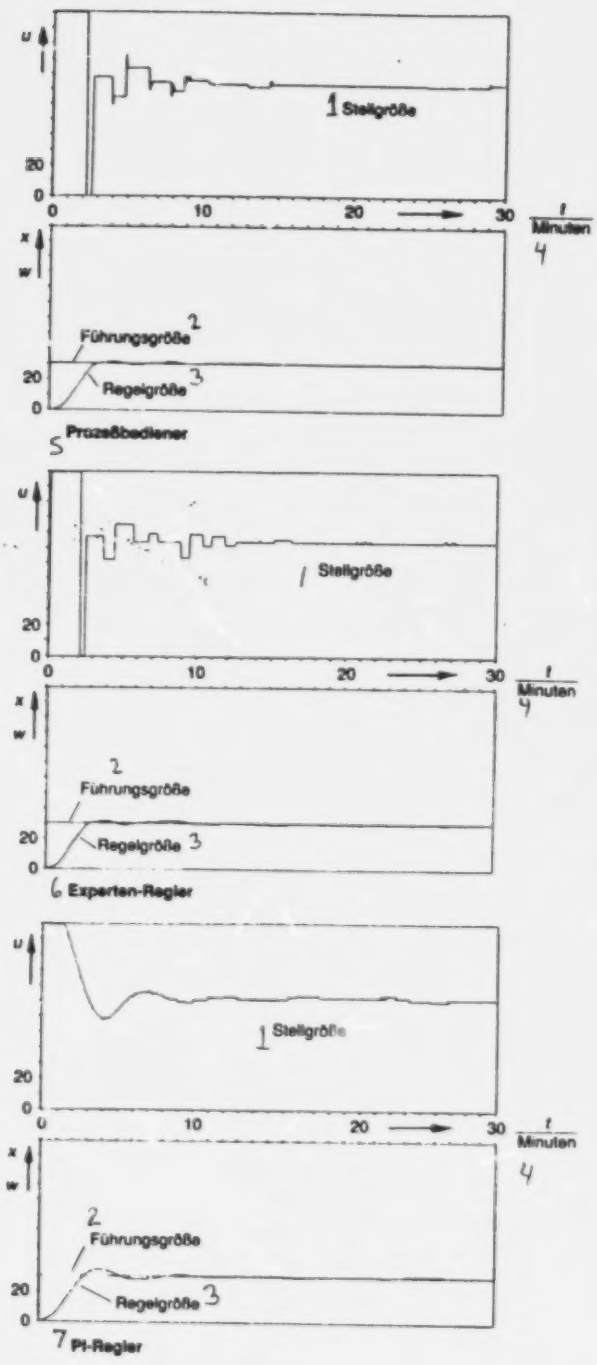
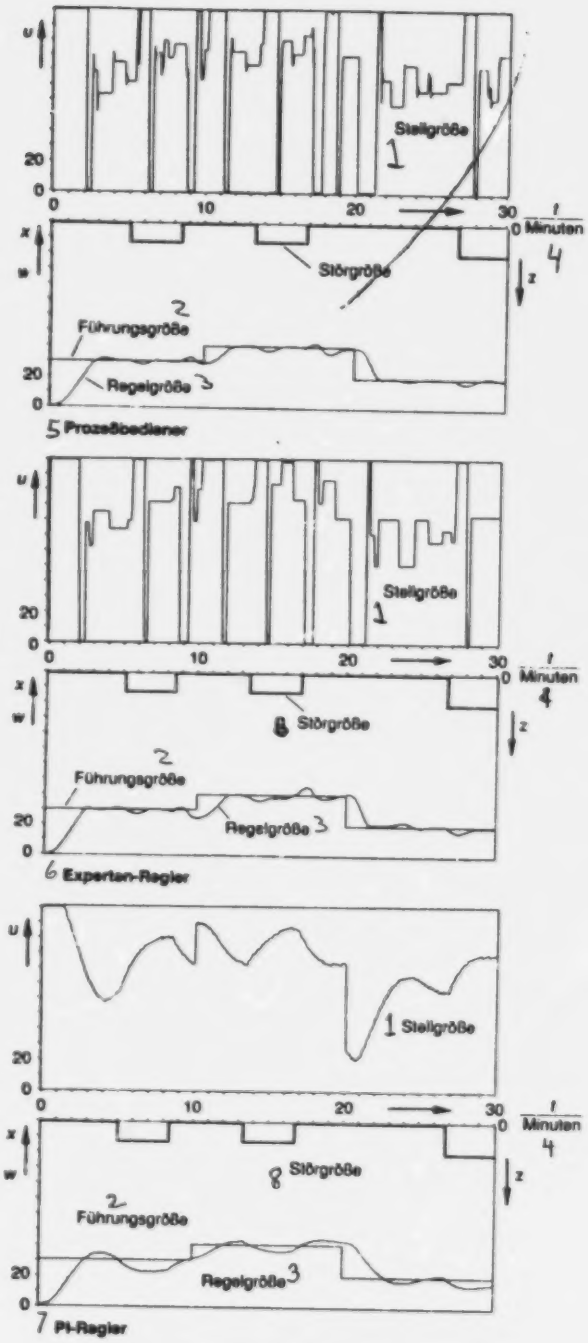


Fig. 7. Comparison of the Expert Controller to that of a Process Controller from Fig. 3.

Key: 1-adjusting quantity 2-control quantity 3-control quantity 4-minutes

recipe, the expert controller contains about 100 rules. For application reasons, the expert controller was made somewhat "softer" by rougher division of the process situations than was possible for the PB. This is shown in fig. 7, which corresponds entirely to fig. 3. Figures 8 and 9 compare PB, expert controller and a conventional PI controller. The PI controller is a "finely tuned" controller based on the adjusting rules of Chien-Hrones-Reswick. Besides a wind-up prevention, it must be provisioned with a constant portion of the adjusting quantity because of the non-linear behavior of the control route. All combinations of adjusting parameters (adjusting of control behavior, adjusting to interference behavior, aperiodic behavior, overshoot behavior) and the mentioned additional parameters were tested.





Comparison of Process Operator, Expert Controller and PI Controller

Fig. 8. Settling in to Desired Value without Disruption

Fig. 9. Behavior for Jumps in Desired Value and Disruptions

Key: 1-adjusting quantity 2-control quant. 3-control quant. 4-minutes 5-process operator 6-expert controller 7-PI controller 8-interference quantity

9. Summary

In [1] it was shown that even passive verbal knowledge acquisition on-line, will not yield a computer-implementable control strategy by the process controller. But it is not true as was concluded in [3], that verbal knowledge acquisition is an unsuitable route to the desired goal. In this paper a successfully developed procedure is described which can be called the "Preparation of a computer-implementable control strategy utilizing verbal communications channel". It has the properties of being cyclic, top-down and incremental. The first level is characterized by:

WHEN <Situation>, THEN <Strategy>,

the second level by

WHEN <Action>, THEN <Expected situation>

and the third level by

WHEN <Situation>, THEN <Action>.

The division of the procedure at the second and third levels is to a certain extent arbitrary.

Appendix: Verbal Protocol of a Skilled Process Operator in the Disrupted Process

Verbal protocol to manipulations 1 to 10 of fig. 3 (PB = process operator, KE = knowledge engineer, SES = stationary required adjusting value, PRZ = proces reaction time).

Manipulation 1

PB: Very small desired value, SES is rather precisely in the middle

KE: What else can one say?

PB: Fully stationary rise will not be attained, that is, the switching difference is quite small, about 6 mm. Braking time is probably 3 mm.

KE: Is that right? You know about the chronic overshoots. At any rate, you have to do something now, right?

PN: Nope, I think one more pixel can come over.

Manipulation 2

KE: I don't entirely understand the rough table.

PB: Given the small rises, everything is very critical. Things have not yet been quite so tight.

Manipulation 3

PB: So, adjusting value in the middle. Now things have to move slowly.

KE: Prediction? (No response).

PB: Something's happening. Now it has to keep going, otherwise we'll be stuck too low. Now we're stuck, we'll have to put something on top. How much do I use? Now we have about 2 mm control difference. So, just 2 cm (relative adjusting value).

Manipulation 4

PB: Now it's moving again.

KE: When comes the counter-manipulation?

PB: We'll wait to see how it goes.

KE: What's supposed to happen with this manipulation?

PB: If things should speed up again, or shorter bars after passing the PRZ. As soon as that happens, switch to braking immediately, given the small control difference present here.

KE: The PRZ is just passing.

PB: So cut manipulation in half.

Manipulation 5

KE: What's supposed to happen now?

PB: Overshoot just a bit with this rise and then a quite orderly bar lengthening should occur.

KE: When do we do something?

PB: As soon as we find the extremum. So, I predict an extremum caused by the (present) manipulation.

KE: Is it already braking?

PB: Maybe we should keep waiting. We could start the counteraction, but it is still a little early.

KE: PRZ is past. If we don't do anything, what will happen? (No response).

PB: There it is. OK, now back up; cut the last one in half.

Manipulation 6

PB: That's too much.

KE: So, half a centimeter.

PB: That'll have to do. The bars are already quite long. Provided my manipulation wasn't too late.

KE: What's supposed to happen now?

PB: Until the end of the PRZ, the medium-length bars drop, then I expect another extremum. Again the difficulty is, if the extremum occurs at the desired value, then I have to go back to before the PRZ.

KE: PRZ hasn't expired yet. If we do nothing, what will happen?

PB: Then it will go up again. We already have bar lengthening. It actually occurred a bit early.

KE: PRZ is now past.

Manipulation 7

PB: It is odd that these bars got long so early. I would say we should set back the SES a little.

Manipulation 8

KE: When do we do something next?

PB: As soon as it gets there again.

KE: So we're not waiting until it rises again.

PB: By no means.

KE: When is it supposed to come again?

PB: We can give it 2 cm (PRZ).

KE: Why?

PB: We already have a little play in it.

Manipulation 9

PB: Adjust SES. That's too much ... (adjustment procedure).

KE: It's breaking through there.

PB: I hadn't counted on that. I would say that's a malfunction. But I'm not certain and let's wait. By no means must it go any lower. If we get stuck here, then it can still go back to the last pulse. But further breakthrough means a malfunction. And there it is.

KE: How much SES?

PB: Just a centimeter higher. It's probably a minor malfunction.

Manipulation 10

New beginning of box strategy.

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